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# Concept of Operations for the Dust Dispenser Spacecraft for Active Orbital Debris Removal

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# CONCEPT OF OPERATIONS FOR THE DUST DISPENSER SPACECRAFT FOR ACTIVE ORBITAL DEBRIS REMOVAL


## ABSTRACT

This document presents the concept of operations for the tungsten-particle dispenser spacecraft and supporting systems used in the formation of an artificial ring of dust for active orbital debris removal. Previous papers explained the ring of dust that increases drag on small orbital debris causing it to decrease altitude and enter the Earth's atmosphere. Because this technique is novel, legal and international issues are recognized to allow the engineering community to become aware of these challenges early in the mission development. A short review of earlier work motivates the mission goals and the size and quantity of tungsten spheres to be dispensed along an orbiting ring 1,100 km circular altitude at 90 deg inclination. Discussion of spacecraft subsystems is capped with a review of spacecraft modes and fault detection. Large capacity launch vehicles are indicated for this mission and launch sites supporting polar orbits are noted. Mission and ground operations support is highlighted along with the suggestion that ground stations near the poles are better suited for this orbit inclination. A chronological discussion of a normal mission is presented. Suggested secondary engineering mission goals are given to detect the structure of the ring and its effectiveness at decaying the orbit debris. This document concludes with a summary listing of guidelines for future requirements vetting.


## INTRODUCTION

### Objective

This document presents the concept of operations for the tungsten-particle dispenser spacecraft and supporting systems used in the formation of an artificial ring of dust for active orbital debris removal. Spherical tungsten particles, or dust, all having one specific diameter within the range of 30-60 microns enhance the drag on very small orbit debris, less than 10 cm, to continually lower the orbit until reentry.

### Principles of the Concept of Operations Document

This concept of operations document is a user oriented document that describes system characteristics of the to-be-delivered system from the user's viewpoint. This document communicates overall quantitative and qualitative system characteristics to the user, buyer, developer, and other organizational elements (staffing, facilities, training, legal, international relations) [1]. Another reference states that the concept of operations document defines the operational capabilities of the system in the absence of specific technical requirements, by giving an overall picture of the operation. It answers the question "what would I do with the system if it were operational now?" [2]


Manuscript approved February 14, 2014.

## Tungsten Particles Used to Remove Small Orbit Debris

The dust dispenser spacecraft is the low-Earth-orbiting spacecraft that dispenses minute tungsten particles into a ring that orbits Earth. The particles enhance the atmospheric drag that orbit debris flies into; thereby, causing a more rapid altitude decay of the debris orbit. The next two paragraphs are quoted from our recent paper to concisely sum up the motivation for the need of a spacecraft to release dust [3].

> Low Earth orbit (LEO) is becoming increasingly populated by orbital debris that is hazardous to operational spacecraft. Orbital debris comes in all shapes and sizes, but NASA has determined any debris between 0.5 mm and a few centimeters to be mission ending, with the larger debris being the source for the smaller ones. The larger debris is trackable and thus collisions with them might be avoided or they may be individually grabbed and removed from orbit by robotic probes. This is not possible with the smaller untrackable debris. Recently, a concept for removing such small untrackable orbital debris with characteristic scale sizes less than 10 cm using micron size tungsten dust grains to enhance the drag on targeted classes of orbital debris has been developed. The basic idea is that the dust will create an artificial drag through hypervelocity collisions with the debris, such that the altitude of the debris can be rapidly reduced. The hypervelocity dust collision with the debris generates high pressure shock waves in the debris resulting in evaporation, melting, fragmentation, and formation of ejecta from its surface. This results in a large negative delta-V that lowers the debris orbit. To maintain dust in LEO for adequate duration requires high-density dust of diameter between 30-60 microns. The novelty is that this will create a 'sweeping' or 'snowplow' effect by a narrow layer with modest amount of dust that can remove large quantities of debris spread over a very large volume. Tungsten was found to be a suitable material, as it is readily manufactured, non-toxic, and inexpensive.
>
> Most small debris (< 10cm) is confined in altitudes roughly between 700-1,100 km. Small debris with altitudes less than 700 km have a fairly rapid orbital decay. Additionally, most debris is concentrated in the popular sun-synchronous orbit. The goal of the proposed debris removal scheme then is to lower the altitude of debris initially between 700 km and 1,100 km to about 600 km or to an altitude below which the natural atmospheric drag can quickly decay their orbit. Releasing micron scale high-density dust into a polar LEO has many advantages for this removal scheme. First, polar orbits generally have small rates of precession so that the dust orbits will be confined to a range of angles about the pole. Second, polar orbits intersect the orbits of the debris population such that the relative velocity between the populations is very large (almost head on collisions). Third, the size and mass of the dust grains are such that solar radiation pressure can create a spread in altitude that is desirable for keeping the volume of the ring small enough to keep the number density favorable for interaction and large enough to ensure sufficient interaction with the debris population.

## Dispensing Region

Earlier analyses found that releasing the particles at 1,100 km circular altitude into a 90° inclined orbit should envelope a large fraction of small orbit debris. Figure 1 presents sketches of the orbiting ring. As the particles decay in altitude over a predetermined duration, for example 12 years, the particles continually collide with both previously impacted debris from the initial particle orbit that has decayed to lower altitude and other debris already in the lower altitude orbit. This snowplow effect enhances the effectiveness of the particles in removing small orbit debris.

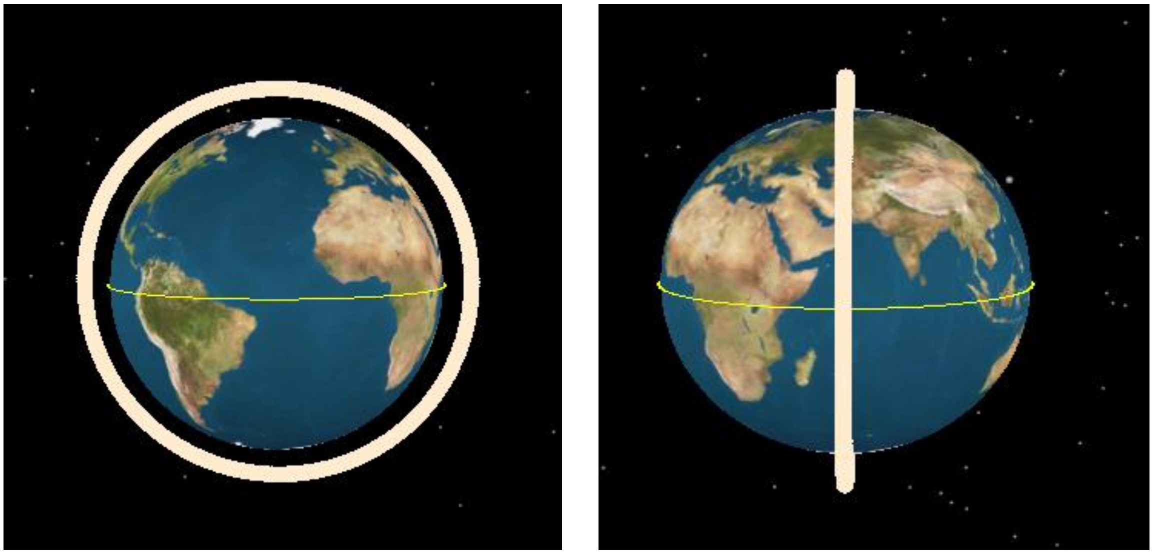

Fig. 1 — Sketches of Particle-Filled Orbiting Ring soon after Initial Formation (thickness not to scale)

The earlier analyses showed the orbiting tungsten particles decay rate is a function of their ballistic coefficient [3]. This is why we desire the particles to have a specified diameter with tight tolerance. For example, having the entire sphere of 30 ± 2 microns diameter in turn yields tight tolerance on the ballistic coefficient. The particles should then decay in altitude at the same rate so as not to grossly distort the ring shape. Additionally, the orbit remains essentially fixed in inertial space because the orbit's inclination remains nearly 90° throughout its lifetime and the right ascension of the ascending node rotates about 10° during the approximate 12-year decay.

**Dust Dispenser Spacecraft**

The main goals of the spacecraft are to contain, transport, and then dispense the tons of tungsten particles in a manner that allows the particles' relative orbital motion to fill the ring with uniform density. If there are no follow-on goals, then the spacecraft should deorbit. A secondary goal of the spacecraft may be to support instrumentation that provides data to estimate the integrity of the ring, for several months to years after ring formation, its early altitude decay, and the effectiveness of this debris remediation scheme. The purpose here is to inform the international space community of the ring's whereabouts and effectiveness should development of ground-based tracking of the ring and the census of very small debris prove fruitless.

We envision the particle release to occur in stages such that the particles are eventually evenly spaced about the orbit. The directional delta velocity applied to push the particles outside the dispenser spacecraft produces beneficial relative motions such that the particles will somewhat uniformly fill out the orbit in-track, cross-track, and along the radial. The approximate extent of this is about 5 km cross-track and 30 km radial. Since the particles are ejected out the back of the dispenser spacecraft within a range of speeds and directions, the particles will enter slight different orbits with slightly different periods. These will eventually fill out the orbiting ring in perhaps 36 days based on a 5 m/s push as shown in earlier analysis [3].

We also expect the spacecraft to incorporate a propulsion system to achieve the mission orbit after correcting for launch injection errors, maneuvering as needed to support particle dispensing operations, maneuvering to support possible secondary goals, and to deorbit after its mission so as not to remain orbit debris.

### Overview of this Report

Because the concept of orbiting tungsten particles to remove small orbital debris by impact is so novel, the next section addresses the legal and international issues to forming a global understanding of this mission's significance and to invite participation by the international space community.

The body of this report covers the concepts of the proposed system. Summaries of the physics behind the tungsten particle collision with small orbit debris leading to debris removal are highlighted. The objectives of the dispenser spacecraft are stated with emphasis on the vehicle subsystems to support the mission, including modes of operation. Suggested launch sites and larger lift-capacity launch vehicles are noted. Mission and ground operations support is reviewed to introduce the breadth of personnel and hardware needed to support the flight. Discussion about operational, organizational, and developmental impacts will also be covered.

A nominal mission is briefly discussed from pre-launch activities to deorbiting the dispenser spacecraft at misson's end.

Because this document is later used to develop some spacecraft and mission requirements, a table of guidelines summarizes parameters that should be refined as requirements are developed. Some additional research topics are mentioned.

## LEGAL AND INTERNATIONAL ISSUES

### Overview

All space-faring nations want orbit debris cleared from space so as not to harm active spacecraft and astronauts on extra-vehicular activities. Our research effort is focused on removal of orbit debris less than 10 cm. The tungsten dust ring should decay from 1,100 km to 600 km in about 12-26 years depending upon ballistic properties. Because 600 km altitude is generally the highest altitude where everything will decay within 25 years, the goal is bring both the tungsten particles and small debris to this altitude [4, p. 218]. Then natural decay will bring both the particles and debris into the Earth's atmosphere for destruction. After the space community agrees on the merits of the dust ring concept, a demanding requirement is to have active spacecraft avoid orbiting opposite to the direction of the particles' orbits. Should a future active spacecraft need to be in an orbit of, say, 1,000 km circular at 90° inclination, it must have a propulsion system and maneuver control to leave its mission orbit as the ring decays through 1,000 km. Several months later, the active spacecraft could return to its mission orbit.

The tungsten particles are <u>active spacecraft</u> (not space debris) while at altitudes greater than 600 km because they are part of the debris removal process. The particles enhance the atmospheric drag surrounding the debris by actively cratering, to roughen its surface, by vaporization of material to affect a small negative Delta V, and by impacting the debris to slow its orbit speed causing it to decay.

Given the strategic importance of this mission, the complete span of international legal, policy, and diplomacy implications should be fully considered when planning and operating this mission [4, p. 337]. The dust dispensing team, including its sponsor, must anticipate these issues to avoid adverse decisions that are likely to be directed from the government leaders, legislators, and the courts of many countries and the international space community.

**Highlights of Various Treaties and Policies**

The dust ring moves through a large volume of space under its gradual decaying altitude for several decades. Presumably, the trillions of tiny active spacecraft will fill and maintain dust-ring shape. There are several space-related international treaties and policies that govern national actions essentially stating space is free for use and without discrimination of any kind. Additionally nations must avoid adversely affecting space activities of other nations. Clearly space-faring nations must agree to this revolutionary debris removal strategy by accepting the constraint to actively avoid the dust ring at the cost of adding a propulsion system aboard their spacecraft.

Summaries from material presented in Reference 4, pages 339-343 are highlighted below.

The Treaty of Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, 1967 forms the basis for most space law. Here are some highlights from Reference 4 that are useful in realizing the non-technical issues with this mission.

- outer space … shall be free for exploration and use by all States without discrimination of any kind…

- nations should have the freedom of scientific investigation in outer space

- nations bear the international responsibility for their activities in space

- launching nations are liable for direct damages to citizens of other nations caused by national and private launch activities

- "A State Party to the Treaty retains jurisdiction, and control rights over their spacecraft, space objects and personnel. In addition, ownership rights of objects launched into outer space, and their component parts, is not affected by their presence in outer space. Unless these rights are relinquished, some argue that peacetime retrieval, alteration of orbit, or any form of interference with foreign space objects would be unlawful without prior consent under treaty and customary international law, no matter how desirable the end result. If strictly interpreted, only a launching State can exercise *jurisdiction and control* of its space objects, even after satellites are defunct and long abandoned, and even if they threaten a particular orbital regime or another satellite with debris. Any entity attempting to remove space junk could run into a claim from a State that the removal is a violation of international law."

- nations must conduct space activities so as to avoid harming or adversely affecting space activities of other nations

- "If one State's space activities pose a potential to cause harm or interference to space activities conducted by another State, consultations should be initiated before they proceed. Consistent with the point, military mission planners should review the 1977 *Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques* … if they anticipate large-scale effects." This convention prohibits all military or hostile environmental modification techniques that might cause long-lasting, severe or widespread environmental changes in Earth's atmosphere or outer space. Each State Party to the Convention undertakes not to engage in military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage or injury to any other State Party."

- widespread is defined as encompassing an area on the scale of several hundred square kilometers

- long-lasting is defined as a period of months, a season

- severe is defined as involving serious or significant disruption or harm to human life, natural and economic resources or other assets

The 1972 *Convention on International Liability for Damage Caused by Space Objects* expands on a topic noted in the *Outer Space Treaty* that launching states are liable to other states for damage caused by space objects (including debris). States are liable only for direct damage caused by a space object. If damage is caused to another space object in outer space, liability is based on fault.

Under the Liability Convention, the US must pay when her space activities injure the property of other nations. US citizens may also recover damages under the Federal Tort Claims Act.

The 2010 US National Space Policy is based on principles of international cooperation – mitigate the dangers of space debris and improve space situational awareness among many other issues.

Here are additional thoughts based on pages 349-350 of Reference 4.

Although the tungsten dust ring is filled with very tiny active spacecraft, the current ability to observe the ring from the ground and define its general orbit and location may not be possible. Space situational awareness of the ring is absolutely essential to mission success and protection of space assets. Current technology cannot detect, or identify, or assess and track these small dust particles. How can cooperative spacecraft, with propulsion, avoid the ring? Should there be no new spacecraft at the ring's current altitude? There are millions of small debris objects, estimated size below 1 mm, that are undetected. This ring will add trillions more small objects. Mission designers want to design their spacecraft for the certainty of collision with the dust. [5]

Again, addressing these topics within the international space community will be harder than the technical issues associated with the mission. Comprehensive support from other space-faring nations will further confirm the magnitude of the small debris issues and perhaps provide global effort in tracking the dust ring, actively avoiding the dust ring, and estimating the reduction of small debris.

"Cooperation allows space-faring States to combine resources and reduce risk, improve efficiency, expand diplomatic engagement, enhance prestige, improve political sustainability of space projects, and provide workforce stability."

The United Nations Committee on the Peaceful Uses of Outer Space provides several forums to introduce the dust dispensing mission and keep the community informed of the mission through the Scientific and Technical Subcommittee and the Legal Subcommittee. We want to continually notify the international space community of the whereabouts of the dust ring and an estimate its success or lack of success in reducing small debris. (The technical aspects of determining the ring's whereabouts and effectualness are today of unknown methodology.)

## CONCEPTS OF THE PROPOSED SYSTEM

### Background, Objective, and Scope

*Background*

Our previous work showed that small orbit debris, less than 10 cm, can be eliminated through deployment of micron-sized particles of tungsten. Tungsten was chosen because of its high density (19,300 kg/$m^3$), allowing for more benefit to the collision with debris (for example, aluminum structure with density of 2,700 kg/$m^3$). That work discussed the mechanical principles of the dust impacting the debris.

The key physics making these concepts practical is the large momentum change to the debris for individual hypervelocity impacts by a high mass density dust particle. The high relative orbital speeds of head-on and side-on collisions generate craters and high pressure shock waves in the debris. Because dust impacts the debris with velocity greater than the speed of sound in the debris material, a high pressure bow shock is created. High shock pressures fragment, liquefy, or vaporize material depending on the energy of the collision. Shock pressure ejects the fragments, liquid, and gas from the microcrater into vacuum as a recoil jet that imparts negative thrust to the debris mass. The dust vaporizes.

This debris momentum change is much larger than that of inelastic or elastic collisions and is not very sensitive to impact angle, as along as a hypervelocity impact occurs. The induced negative thrust is the key feature resulting in altitude reduction. The dust-induced drag force on the debris is magnified above a simple collision and recoil because of the additional effects of the high shock pressure.

The efficiency of this dust-based debris removal concept is directly proportional to the ratio of debris momentum change to dust momentum. In turn, this sizes the amount of dust to be dispensed into the orbiting ring. As this is written in 2014, separate research continues to determine this ratio to better estimate the mass of tungsten needed for the ring.

Although further research is also expected to better define the particle diameter and quantity, to help motivate discussions for operations, we estimated the orbiting ring uniformly filled with 10 metric tons of tungsten particles of 30-micron diameter. This spherical particle has a volume of $1.41372 \times 10^{-14}$ $m^3$ and mass of $2.7285 \times 10^{-10}$ kg. Ten metric tons or 10,000 kg yields 36.7 trillion tungsten spheres. A solid block of tungsten with a mass of 10,000 kg has a volume of 0.518 $m^3$. The packing for the spheres would be of larger volume. Tungsten spheres of this small size may not be easily produced and tungsten dust particles may suffice.

As a motivation to our guideline of a tight tolerance on the ballistic coefficient of the tungsten particle, achieved through its spherical diameter, the curves shown in Figure 2 demonstrate the different resulting altitude decay as function of diameter. Note both that smaller diameter spheres have a shorter lifetime than larger diameter spheres and the separation of years of lifetime based on the diameter (30-, 45-, and 60-micron diameter plotted left-to-right). One can infer that tight tolerance on size is important to predicting the lifetime of the ring. Pretend there was a wide-range of particle diameters, for example between 30-60 microns, within the ring. You can see that the ring's density and shape would widely spread over hundreds of kilometers negating the denser ring's benefit. The ability of the ring to stay together over its lifetime is a key requirement to the efficiency of this process.

The bulk density of the 1,100 km altitude orbiting tungsten ring in Figure 1 is about $3 \times 10^{-13}$ kg/$m^3$, or about 1 particle in a cube 10 m on a side, which is the atmospheric density at approximately 550 km altitude. The ring has enhanced the atmospheric density and therefore the drag on debris.

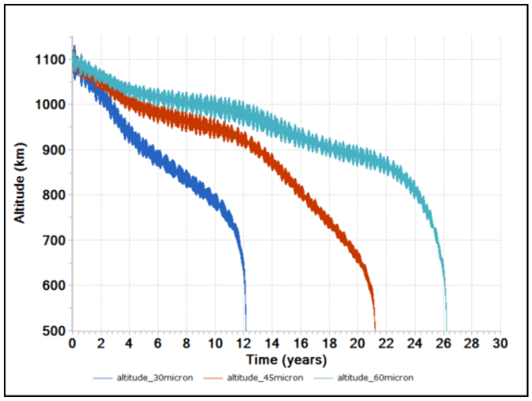


Fig. 2 — Altitude Decay Lifetime of Three Different Particles Beginning in the Same Orbit from 1,100 km

Another consideration for the selection of a 30-micron diameter particle is the 25-year guideline to the removal of spacecraft after they have completed their mission. Although the guideline refers to maneuverable spacecraft, of which the tungsten dust and debris are not maneuverable, we do not want to have dust in space too long.

The following text was copied from a recent report of the National Research Council to highlight the 25-year guideline to removing spent spacecraft from orbit [6, p. 10].

> One of NASA's major mitigation standards has been that "maneuverable spacecraft that are terminating their operational phases at altitudes of less than 2,000 km above Earth shall be maneuvered to reduce their orbital lifetime, commensurate with 25-year low-Earth orbit lifetime limitations." The reason for this 25-year rule was that is has been recognized since the beginning of the program that an increasing accumulation of non-operational spacecraft and upper stages would inevitably lead to increasing collisions involving those objects and would become the major source of small debris. NASA's goal was to gain both national and international acceptance of the 25-year rule.
>
> Yet although the orbital debris mitigation guidelines developed by NASA were gaining wider acceptance by the space community, an increasing number of studies, both national and international, were coming to the conclusion that even absolute compliance with the 25-year rule would be insufficient to prevent the debris population present below 2,000 km (LEO) from continuing to increase as a result of random collisions involving non-operational intact debris.

Returning the Figure 2, we can see that with these sizes of particles their decay to about 700 km is driven by their respective ballistic coefficient. From 700 km and lower, their mission effectiveness is diminished as they rapidly decay. Presumably, the particles would be dispersed and not be threatening to the International Space Station and other manned and unmanned active spacecraft closer to Earth.

As the dust within the ring decays from 1,100 km it collides with debris originally at the lower altitude and repeatedly hits earlier debris that lowered orbit due to momentum loss. This is visualized as a group of snowplows in a staggered alignment. The leading plow pushes snow in front of the following plow and so on until the snow is pushed onto the roadside. The novelty is that a small ring with modest amount of dust can remove large quantities of debris spread over a very large volume.

*Spacecraft Objective*

The goal of the dust dispenser spacecraft is to carry to mission orbit and then dispense the many tons of tungsten particles. As secondary goals, the spacecraft may have sensors and telemetry to downlink videos of the dispensing operations, collect data applicable for estimating the density within and outside the ring, repeatedly maneuver to fly the sensors throughout the orbiting ring, and then deorbit.

This document focuses on the concept of operations for the tungsten-particle dispenser spacecraft, which includes what the spacecraft must accomplish throughout its lifetime. The concept of operations description can be used to form design and mission requirements for the vehicle and its mission operations.

*Scope*

The depth and breadth of material generally follows the formal outlines given in various preparation guides to concept of operations documents. As this is a proposed new system, there cannot be discussion of a current system or justification for changes to the existing system. Not surprisingly, the previous discussion about international treaties and policies may likely force overarching constraints onto the spacecraft and its operations. These are unanswered issues at this time.

**Description of the Proposed System**

This orbital debris removal system has several large interdependent components: the dispenser spacecraft and its capabilities, the tungsten particles, the launch site and vehicle to boost the spacecraft, and the mission and ground operations support.

**Dispenser Spacecraft**

The concept for the dispenser spacecraft to support its primary goal includes propulsion to refine the orbit and deorbit at end-of-life, capacity to hold the weight and volume of tungsten, mechanisms to dispense the particles in a phase-released manner, command and control systems, and a consideration of launch vehicle lift capacity and fairing size. To support secondary goals of various concerns and particle detection, the dust dispenser spacecraft needs to provide structural mounts, proper sensor orientation, command and control, telemetry, and propellant to maneuver throughout the ring for several months. Additional ground support is needed to operate the secondary mission.

A heavy single spacecraft may be a cost-effective approach, although two spacecraft sharing half the mass of the required tungsten load may offer more choices among launch vehicles. In either case the spacecraft will need a configuration and <u>structural design to support the payload</u> and its mission along with the required systems for <u>propulsion</u>, <u>attitude determination and control</u>, <u>thermal control</u>, <u>power</u>, <u>guidance and navigation</u>, and <u>telecommunications</u>. Other necessary onboard systems <u>include mechanisms</u>, <u>command and data handling</u>, <u>and fault detection, isolation and recovery.</u>

The particle containment and dispensing system is the main payload of the spacecraft. This system needs to hold and dispense 10,000 kg of tungsten particles of microscopic size, perhaps a year or more before release. None of these fine particles should leak from the system thus avoiding contamination to other parts of the spacecraft. One mission-ending effect is to cause shorting within electrical systems. During launch and early orbit rectification of the spacecraft, the particles should not slosh around inside their containers and later, upon release, the particles should move away from the spacecraft and each other. They should not have been so compressed within the container that they stick together at ejection by the dispenser.

Other payloads are the various devices to collect data on the effectiveness of the releases and help estimate particle density within the ring. Data should be collected for the duration of the release of all particles. This might be accomplished with pictures and video of the sunlight glint off the particles. Additional sensors could be used to estimate the density of the particles from the spacecraft, perhaps several months after particle release when the particles are uniformly dispersed throughout the ring. With orbital maneuvers, the spacecraft and sensor might remain near or in the ring for one year continuing to estimate particle density and perhaps witness myriad collisions between tungsten particles and debris.

The following subsections further describe some of these systems.

*Particle Containment and Dispensing System*

The particle containment and dispensing system is the spacecraft's primary payload and significant investment in the design, analysis, and testing will be necessary to further define this system. The containment of this large mass (10,000 kg) of very small spheres (30 micron diameter) with no leakage is required beginning when the device is packed, perhaps a year or more before release. The release is to be opposite the spacecraft's orbit direction – out the rear.

One representative case of particle release is summarized from Reference [3]. In 24 hours, the spacecraft makes 6 releases of dust at intervals of 4 hours. One-sixth of the particles (1,667 kg) are released each time. The magnitude of the impulse given to the dust follows a linear probability distribution function with magnitudes between 0.5 m/s and 5.0 m/s. The angle of release is uniformly distributed within the confines of 5° from the negative of the spacecraft's velocity vector. There is also a uniform distribution of 360° about the cone's azimuth. See Figure 3 for an illustration and histograms of the magnitude and direction of the velocity impulse (dv) and half-cone angle (θ). After each release, the spacecraft maneuvers 60° in true anomaly, then actuates the next release.

During this mission mode, it is expected that the spacecraft pitch once per orbit to maintain the dispenser door in the rearward direction. There will be large changes in spacecraft mass properties as the dispensing operations progress.

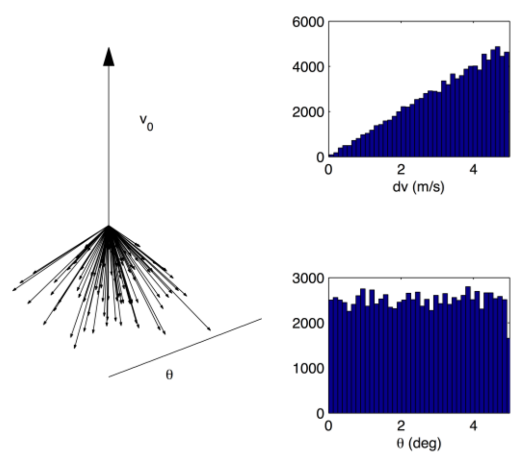


Fig. 3 — Distribution of Delta V Given to Particles to Cause Them to Exit the Spacecraft and Form the Ring

Because the particles are ejected with a range of velocities, the particles will enter into slightly different orbits with slightly different periods. These different periods contribute to filling out the ring. This concept of operations needs to be more comprehensively analyzed, along with the dispenser's design to assure this will perform to fill out the ring. Also, it may be that each dispensing operation perturbs the spacecraft's orbit enough to warrant maneuvering the spacecraft back to the desired dispensing orbit and the next 60° true anomaly location. It will likely require more than 4 hours completing the orbit determination process and defining the corrective maneuvers.

### *Propulsion System*

If the launch vehicle does not insert the dispenser spacecraft within the required orbit tolerance, the spacecraft must maneuver to correct the injection errors. Additionally, the propulsion system will be needed to reset the orbit and spacecraft location after each dispensing event. After the dispensing events are finished, the spacecraft's other sensor payloads could be used to investigate the effectiveness of the ring. Propulsion may be needed to maneuver the spacecraft around the ring (vary true anomaly), or to place the spacecraft in an orbit maybe several kilometers lower than the ring, to make data collections from the circumference of the entire ring. Sampling may take a year to complete. Maybe some debris is observed being continuously hit by the dust and the propulsion system can follow the debris for awhile.

To avoid the spacecraft from becoming orbit debris itself, the propulsion system will need the additional energy and Delta V to affect a controlled descent into the oceans.

### *Other Payloads*

Sensors to observe the entire dispensing operations, months later the formed ring, and finally estimate particle density within the ring are useful science measurements as input to efficiency analysis. Optical sensors for visualizing the dispensing operations seem appropriate. There may be useful contact sensors that produce data, which can be used to estimate the density of the formed ring. Perhaps known debris is in the correct orbit to be pummeled by the particles and spacecraft can orient sensors to observe this interaction.

The secondary mission plan includes taking particle count, or density measurements, or mass flux for several weeks before dispensing and several weeks after dispensing.

### *Configuration and Structural Design*

The dispenser spacecraft will require the strength to support the particle container and dispenser system. The structure will also need to support the interior components, such as the propulsion system and its forces and exterior components such as the sensors and solar panels. Upon launch vehicle and fairing geometry selection, the dispenser spacecraft configuration must support the load paths and fairing size.

The spacecraft will experience large changes in mass properties due to dispensing operations. There may be need for sensors devoted to monitoring the dispensing processes and would be especially useful if a partial dispensing occurred.

*Attitude Determination and Control System*

The attitude determination and control system will likely provide 3-axis control. The spacecraft will need to maintain a pitch rate of once per orbit during particle release operations. Additionally, the spacecraft will need to maintain attitude during thrusting operations to accurately change orbit and for sensor pointing toward the dust ring. There will be other modes for attitude control during spacecraft rectification, safe hold, and sun pointing. Special consideration must be taken to maintain the attitude during dispensing operations where large changes in mass properties occur. This system must also be designed for full attitude control should an undesired partial dispensing occur.

*Thermal Control System*

This system maintains temperature of all spacecraft components within design limits throughout the mission lifetime, subject to a range of environmental conditions and operating modes. The orbit will expose the spacecraft to days of full sun and most days of having the spacecraft move through the Earth's shadow each orbit.

*Power System*

This system generates and stores electric power for use by the other spacecraft systems. For the dispenser spacecraft, power will likely be generated by solar cells and storage within batteries. From these sources, the regulation and distribution of stable and uninterrupted power to the systems continues throughout mission lifetime. The systems have various requirements for the regulation of voltage, frequency, and current, and their cleanliness.

The power system must provide electrical protection to other systems and within the power system itself. There may be an array of mechanisms to deploy and aim the solar arrays.

*Guidance and Navigation System*

Guidance is the control of the spacecraft's path. Navigation is determining the current position of the spacecraft and planning the path relative to a frame of reference as a function of time. Depending upon the level of onboard autonomy, these functions may be handled by the mission operations team. Guidance includes correcting orbit insertion errors, maneuvering (if necessary) between dispensing operations, maneuvering to carry the density-type sensors throughout the particle ring, maneuvering to maintain orbit, and finally to deorbit the spacecraft.

The need to change the orbit for maintenance and dispensing will be decided by the mission operations team because the current orbit may be acceptable to achieve particle dispensing objectives and science data collection. Whether the dispensing is proceeding as expected or not, maneuvers to reposition the spacecraft should be made in concert with the plan of the dispensing sequence. Similarly, it may be that the spacecraft needs to maneuver in some manner to support observation of the dispensed particles or collecting particle density data. These maneuvers should be made in concert with the plans for science collection.

Navigation includes orbit determination, which is enhanced with a mix of data obtained from onboard Global Positioning System (GPS) receivers and from ground-based surveillance and tracker sensors such as radar and ranging radio signals.

Here are examples of ground-based data used in the orbit determination process:

- Tracking radar sensors provide range and range-rate time-tagged measurements.

- Ranging signals from the ground station are sent to the spacecraft on the uplink and a response signal from an onboard transponder is received on the downlink.

International ground-based navigation systems are the Space Surveillance Network, Russian Space Surveillance System, International Scientific Optical Network, European Space Surveillance and Tracking System, Indian Deep Space Network, and the Chinese Space Surveillance System [4, pages 593-594].

Here are examples of space-based data used in the orbit determination process:

- The dispenser spacecraft needs an onboard Tracking Data Relay Satellite System transponder for high-precision range and range rate tracking of the spacecraft relative to the tracking data relay satellites. Highly accurate estimates of the tracking data relay satellites' position and velocity are available, enabling the ground segment to determine the dispenser spacecraft's position.

- Position (latitude, longitude, and altitude) of specific receivers placed on the spacecraft are determined from the signals sent by navigation satellites.

International space-based navigation systems are the Global Positioning System, Russian GLONASS, European Galileo, Indian Regional Navigational Satellite System, Chinese Beidou-1, Tracking Data Relay Satellite System on-board navigation system, and the Doppler Orbitography and Radiopositioning Integrated by Satellite [4, pages 595-596].

*Telecommunications and Command and Data Handling Systems*

This system accepts ground commands from the uplink and downlinks spacecraft health and mission data to ground stations assigned to this program. Onboard hardware includes the transmitter and receiver radios, antennas, and wiring.

The communications system is closely tied with command, control, and data handling. As the spacecraft's receiver accepts uplinked command instructions from the ground, the onboard command processor acts on these instructions. As flight plans are loaded on the bus, the onboard processor checks for validity. Typical commands include turning various systems on and off via the power switching unit.

The spacecraft is in a low orbit that has a period of approximately 107 minutes. There is limited duration of contact with a single ground station. Depending upon the geometry, the contact may be about 10 minutes. During this contact commands to the spacecraft need to be sent and confirmed and then the spacecraft can transmit to the ground its stored and real-time health status and stored and real-time mission data. There can easily be a mismatch between the rates of data acquisition by the sensors and downlink opportunities. For example, should there be an optical system recording high-resolution video and still images, the downlink capacity may not be available to support the large volume of data. Even a high data transmission rate from the spacecraft to the ground may not matter given one mission ground station. Several ground stations may help, along with data compression techniques. Onboard storage of mission data could alleviate the downlink bottleneck by spreading the transmission over several days. Early orbit rectification of the spacecraft and the particle dispensing operations are times when longer periods and larger quantities of uninterrupted communication with the ground are highly important.

*Spacecraft Modes*

A mode is a particular functioning arrangement or condition. Applicable to the dispenser spacecraft, the concept of modes allows us to describe and categorize the different conditions the spacecraft will operate during its lifetime. Table 1 lists the names of the spacecraft modes and their definitions, which covers all conditions from ground processing to spacecraft disposal. There are certain expectations of the system configurations and responses and of the mission crew when each condition is evident. The mission crew will define these configurations and expected responses during the program design and refine the configurations during testing and mission operations rehearsals.

Table 2 lists the same names but different definitions applicable to the flight software. Flight software resides in many pieces of hardware within the spacecraft: central processor for the bus, payload computer, control system, power management system, and other systems. At the lowest level, the software that resides in a specific system's hardware may control only that box. At higher levels, the software performs data processing and housekeeping functions, interprets and executes ground commands, and synchronizes the functioning of all the other processors distributed within the spacecraft.

*Fault Detection, Isolation and Recovery (FDIR) System*

Fault detection, its isolation, and recovery from the fault are part of overall spacecraft health management. This system resides in different forms in the flight hardware, the flight software, and the mission operations center. The main goal is to effectively detect faults and accurately isolate them to a failed component or process in the shortest time possible. This capability leads to a decrease in diagnostic time or downtime in general, resulting in increased system availability. Effective fault detection, isolation and recovery can keep a complex system or process running and is especially beneficial for a spacecraft where maintenance is impossible.

Flight hardware FDIR can include watchdog timers, on-chip built-in-tests, and memory scrubbing. Flight software FDIR can include sequence checking, diagnoses and response and re-plan, and then continue the action.

Inherent within the processing software is the concept of fault protection. There will be processing anomalies and hardware faults that can be dealt with onboard the spacecraft to ensure the spacecraft does no further harm and can be restored to OPERATIONAL mode. The software may put the spacecraft into SAFE or SURVIVAL mode.

Fault protection is the use of cooperative design of flight and ground elements (including hardware, software, procedures, etc.) to detect and respond to perceived spacecraft faults. Its purpose is to eliminate single point failures or their effects and to ensure spacecraft system integrity under anomalous conditions. [7]

Onboard, FDIR are the autonomous actions the bus takes. FDIR tells the system what to do; it does not do the work of the system.

Within the umbrella of fault protection, the first two branches are fault avoidance and fault tolerance. Fault avoidance includes good, robust, design features, significant ground-based testing before flight, and onboard autonomy including constraint checking. Fault tolerance includes application of redundancy, fault containment, graceful degradation, being alert to the issues of fault masking, and FDIR. Finally, there are ground-based, flight hardware, and flight software FDIR considerations.

Table 2 lists the flight software modes. The transition among these modes is diagramed in Figure 4, which shows the flow for commanded transitions, and Figure 5, which shows the flow among autonomous transitions.

Ground-based FDIR can include telemetry alarm checking, telemetry trending and analysis, and contingency plans and procedures.

Table 1 — Suggested Modes for the Dispenser Spacecraft's Hardware

| Mode Name | Description |
|---|---|
| OFF | unpowered, spacecraft receives no external power from the ground or launch vehicle<br>OFF mode is used for ground storage and transportation and possibly at the end of the mission upon deorbit |
| ACTIVATION | this mode refers to further turn-on and warm-up, perhaps unfolding solar panels, communications antennas, initiating GPS and attitude determination and control<br>ACTIVATION occurs after separation from launch vehicle and ends when the spacecraft temperatures, biases, and currents have stabilized within specified operational limits, commands flow from the ground and science, engineering, and housekeeping data flow to the ground |
| CHECKOUT | this mode begins after ACTIVATION and are the steps used to bring the spacecraft to the OPERATIONAL mode, this is the time for testing the full functionality of all systems to assure full availability |
| OPERATIONAL | spacecraft is fully functional |
| SAFE | secure the hardware from possible damage due to certain anomalous conditions<br>emergency low power consumption, spacecraft points and maintains the solar panels toward the Sun, operational power is turned off, survival heaters might turn on, two-way telemetry links are maintained, power system anomalies and attitude system anomalies are examples of conditions which could result in entry into SAFE mode, there are likely to be several autonomous conditions that cause entry into SAFE<br>manual control is required to leave SAFE mode and, as necessary, return to ACTIVATION or CHECKOUT mode |
| DIAGNOSTIC | investigate the cause of a condition or problem<br>spacecraft may dwell on and transmit to the ground any science, all engineering, health, and status telemetry, there may be data rate limits and long duration tests of a specific subset of functions, perhaps not everything has to be transmitted to the ground<br>DIAGNOSTIC is a flexible mode to create troubleshooting or configurations yet unforeseen, this mode supports housekeeping and software updates, |
| SURVIVAL | to remain in existence, must maintain power at a survival level (for survival heaters)<br>SURVIVAL mode is entered when a critical power shortage has been identified and is a low-power condition from which the spacecraft can eventually recover to full operational status, only those functions and hardware required for safety, diagnostics, and recovery will be powered, science-type data collection and processing is off |
| DEORBIT | actions used to dispose of the spacecraft by causing the spacecraft to reenter the Earth's atmosphere and splash into an ocean<br>approximately one year after dispensing, science operations are complete, the spacecraft's altitude is approximately 1,100 km and maneuvers occur to lower the altitude to perhaps 200 km circular or 200 x 1,100 km elliptical, thrusters are activated to aim the spacecraft through the atmosphere, avoiding habited land areas, with a very high probability of splashing into an ocean, the spacecraft may be commanded into the OFF mode after thrusting as the final command |

Table 2 — Suggested Modes for the Dispenser Spacecraft's Flight Software

| Mode Name | Description |
|---|---|
| OFF | inactive |
| SAFE | mode the flight software is in when first powered on, or after any power cycle, or a critical anomaly<br>configure the flight software tables (telemetry, fault detection, isolation and recovery) |
| ACTIVATION | mode is the first step in preparing the spacecraft for operations<br>allows the spacecraft to be rectified, oriented to the Sun, power configuration established, turns hardware on or off |
| CHECKOUT | mode is the second step in preparing the spacecraft for operations<br>allows the various parameters in the hardware to be configured for operations, science, housekeeping, and engineering data are transferred as checkout of the mission downlink<br>configure the receivers and data handling system |
| OPERATIONAL | this is the normal mode for the spacecraft, where science and housekeeping data is continuous and available for downlink |
| DIAGNOSTIC | in the event of an anomaly that is not critical, flight software transitions into this mode to allow the ground to troubleshoot the anomaly, this mode does not restrict commanded actions as do the other modes, this mode allows thorough analysis and information gathering while leaving the instrument in a near operational condition, survival power may be needed in the event loads are turned off, survival power is not automatically turned on in this mode, this mode is applicable to any and all valid spacecraft actions but not for and during the critical dust release and maneuvering mission actions |
| SURVIVAL | same as SAFE |

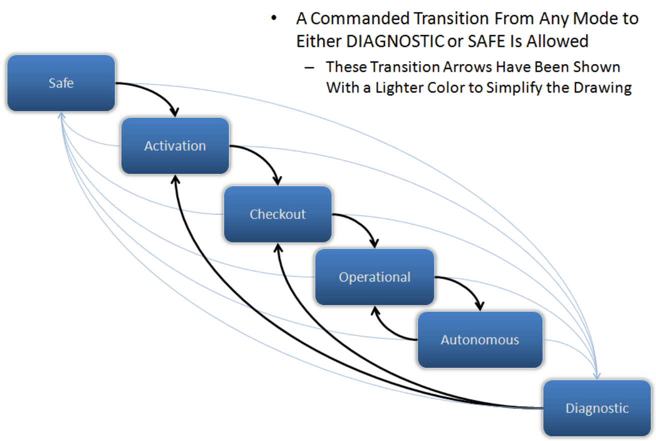


Fig. 4 — Flight Software Mode Transitions Via Command

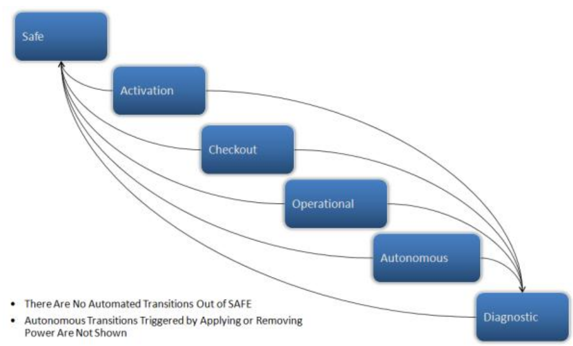


Fig. 5 — Autonomous Mode Transitions

**Tungsten Particles**

Tungsten was selected and its properties used in earlier analyses primarily because of its high mass density and relative abundance. Higher mass density equates to higher efficiency of the collision; therefore, lower total mass of particles is needed relative to other material. Our technique of removing small orbit debris by impacting debris has been described in other technical papers and earlier in this document.

Also noted earlier was the beneficial effect of having identically-sized tungsten spheres: the orbiting ring decays at the same rate. Different sized particles will experience differential drag and will cause the ring to spread from other particles and yield a less compact or less dense orbiting ring, diminishing the benefit of the concept.

From several website searches of precision ball manufacturers, the industry appears to be able to produce tungsten spheres at or very near the 30 micron diameter. These websites note that there are several important parameters in the specification of the ball. Some parameters include the size and tolerance of the mean diameter, sphericity (deviation from a true sphere), surface integrity (surface smoothness and freedom from defects), and surface hardness.

### Launch Site and Vehicle to Boost Dispenser Spacecraft

Some launch sites around the world that support the 90° orbit inclination are in Alcantara, Brazil; Kourou, French Guiana; Sea Launch; Kodiak, Alaska; and Vandenberg, California [4, p. 862]. There may be other sites which also must meet range safety requirements.

Assuming the payload has a mass of 10,000 kg, the entire spacecraft might have a mass of 13,500 kg or more. The overall dimensions of mass and volume must fit into the fairing of a large rocket. This large mass is served by only a few launch vehicles carrying the entire dispenser spacecraft into 1,100 km circular at 90° inclination orbit. The launch vehicle should place the spacecraft into the mission orbit, where the orbit tolerances are suggested in Table 4 in the Guidelines section. The spacecraft's propulsion system maybe expected to correct small injection errors. Some launch vehicle's that have the lift capacity are the Delta IV-H [8, p. 2-43], Atlas V-551 [9, p. 2-116], and Ariane 5 [10, p. 2-7]. The H-IIB may also have the capacity for the mission [11].

### Mission and Ground Operations Support

There are several mission objectives for the dispenser spacecraft: to dispense the dust particles at different locations along the orbit track, fly within the ring to sample its density and perhaps witness impacts on debris, maybe for a year, and finally safely splashdown in the ocean as its flight ends. Among myriad other considerations, mission success requires constant careful planning years before launch and throughout the mission, which continues until the particles reenter. We discussed the international cooperation necessary for initiating this debris-removal mission and this will follow through the entire mission lifetime. This is not an American-centric mission. Decisions must be made on executive management, costs and budgets, selection of the spacecraft manufacturer, launch site, location of the mission operations center, and agreements with ground stations for communications. This includes the global network of tracking and observation for estimating the tungsten ring's integrity and the decreasing population of small debris particles to judge the effectiveness of this technique.

The expectation of how to fly and operate the spacecraft should be designed in from the early stages because spacecraft design decisions impact how operations are conducted. There is a cost-trade relationship between operable designs on the spacecraft vs. the cost of operations on the ground. Sometimes the builder of the spacecraft is not the same organization that will operate the spacecraft. Operations need to be closely involved with the conceptual and detailed design of the spacecraft and ground systems and later their testing and procedures development. Mission operations development covers the period from mission concept (a future Operations Concept Document) until launch and the completion of the launch and early operations, and continues throughout the mission.

Ground communication and control with the spacecraft and payloads, monitoring and analyzing their condition and success in accomplishing tasks, and sending commands in real-time or for future execution is the core of mission operations and ground support. This is expanded by the desire to monitor the tungsten ring and the changes in the population of small orbit debris. Reference [4, p. 905-908] has an extensive discussion of this support and will be used here to guide applicability to the dust dispenser mission. Eight mission operations functions perform distinct tasks during the mission and are paraphrased here.

1. Mission Planning and Scheduling consists of the facilities, equipment, software, and personnel trained to plan, schedule, and program the activities of the space and ground segments. This function provides the master schedules, generates the pass plans for configuring and performing real-time operations, and creates the command loads.

2. Test and Simulation consists of the facilities, equipment, software, and personnel trained to support operations training and rehearsals, test command scripts before uplinking to the spacecraft, perform anomaly resolution and software maintenance, and test system modifications and enhancements. This function often uses an operational test bed, which integrates duplicate spacecraft or ground station hardware and flight software with environmental software models. The test and simulation function is used during spacecraft and ground system integration and test, and then operation rehearsals before and sometimes after launch. The operational test bed need not reside in the mission operations center; in fact, it will usually reside in the spacecraft factory electronically or virtually connected to the operations center. For this task, the test and simulation function typically interfaces with operations center at the command and telemetry frame or packet level such that the test and simulation functions look like an actual spacecraft or ground station telemetry stream and responds to commands in some realistic or representative fashion. The simulators can be used after launch to test command loads prior to transmission to the spacecraft and execution on board, to assist with anomaly resolution, and flight software maintenance.

3. Ground Segment Operations consists of the facilities, equipment, software, and personnel trained to monitor and control the mission's ground network, including both the ground stations and the connecting communications network. The ground segment reliably supports spacecraft passes, including tracking the spacecraft (antenna control), and collection, transferring, and storing its data. This function ensures that the network is properly configured to support each scheduled contact. Although the ground stations support real-time operations, they might be fully automated and do not require monitoring as long as they were configured to the mission requirements beforehand to execute the pass.

4. Real-time Flight Operations consists of the facilities, equipment, software, and personnel trained to provide real-time monitoring, command and control of the spacecraft in the mission operations center during ground contacts. This function monitors the spacecraft during the real-time contact, ensures that commands and uploads are successfully received and executed by the spacecraft, and that both state-of-health and payload telemetry are downlinked as planned.

5. Spacecraft Operations consists of the facilities, equipment, software, and personnel trained to provide the engineering support for the spacecraft bus during the mission. These engineers monitor and analyze the spacecraft state-of-health data contained in the downlinked telemetry to determine and ensure spacecraft safety and mission effectiveness. They use processed telemetry data and ground network data for analysis to detect any anomalous spacecraft subsystem or ground network performance, and to assess long-term trends. Trending analysis can help prevent malfunctions by noting and correcting potential problems before they reach a critical stage. The spacecraft operations engineers form the core of the anomaly resolution team and generate regular status reports on the health and condition of the spacecraft.

6. Payload Operations consists of the facilities, equipment, software, and personnel trained to monitor and maintain the health and welfare of the payload, to monitor its performance, and sometimes any ground data processing and ground-based quality measurements, in accomplishing the mission objectives. In this mission, the payload is to be activated in a series of particle releases watched by cameras to collect and downlink still or video images. Later, as the spacecraft orbits within the ring, optional payload sensors collect data to estimate the density of the ring, damage to the dispenser spacecraft from the particles, and possibly more images of the tungsten particles striking debris. Payload operations develops schedules for real-time operations and provides uploads of commands to accomplish these mission objectives.

7. Flight Dynamics consists of the facilities, equipment, software, and personnel trained to determine and predict the spacecraft's orbit and position in space, and also to determine or calculate its orientation. The orientation or attitude determination and control function may be done on the spacecraft, the ground, or a combination of both. Engineers within this team determine the spacecraft's orbit using tracking data received from ground stations and then use the state information to predict where the spacecraft will be for maneuvers and all the payload operations. This provides four-dimensional (position and time) information to know where and when events and activities are to occur or did occur. Both orbit and attitude changing maneuvers are developed within this team. A new opportunity to avoid collision with larger space debris, that may be applicable, is to work with the Joint Space Operations Center, who maintains a catalog of tens of thousands of objects in orbit roughly 5 cm or larger. The flight dynamics team may need to provide the orbit of the dispenser spacecraft to the Center and, in turn, the Center will predict if there are objects expected to come within a close zone around the spacecraft.

8. Data Processing consists of the facilities, equipment, software, and personnel trained to handle the spacecraft telemetry received at the operations center and process it into a usable form, archive the data, and distribute the data. This function converts the telemetry into engineering units to be displayed by the real-time system for the system engineers to perform trending and analysis.

Mission operations consist of the continual cycling through planning, execution, data management, analysis, and, as needed, anomaly resolution processes.

Figure 6 [4, p. 918] provides an organization chart of typical groupings of functions and common staff positions that fulfill each function shown in parentheses. This chart helps with developing a staffing plan.

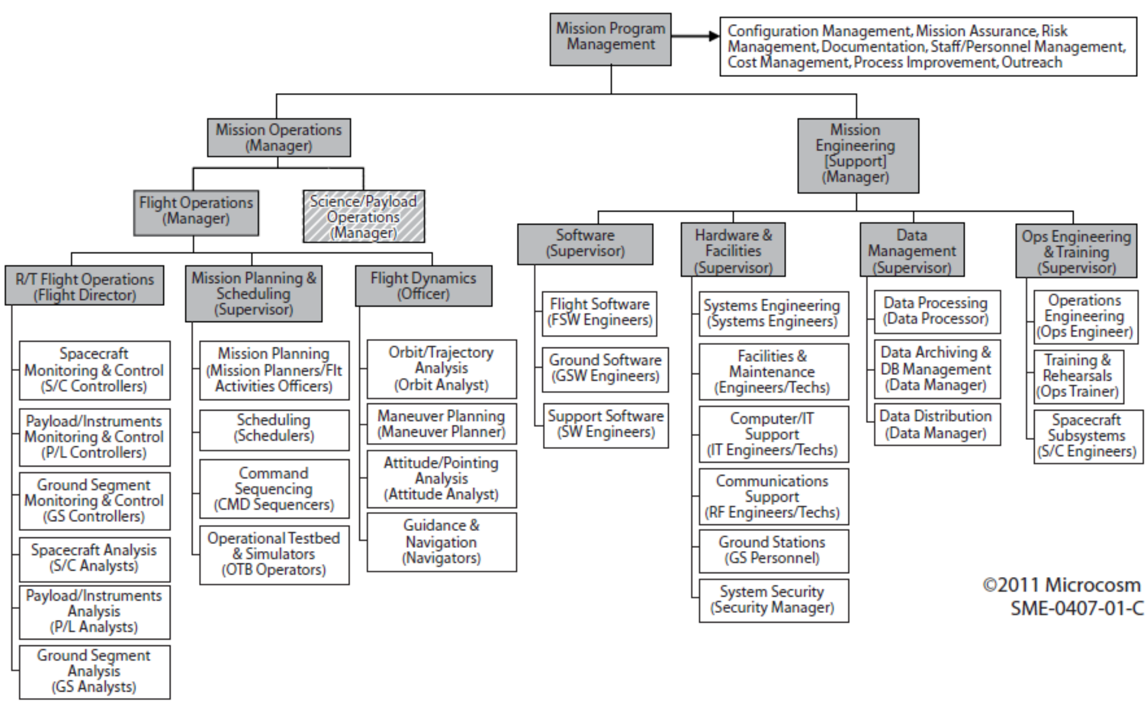


Fig. 6 — Sample Mission Operations Organization from [4, p. 918]

### *Mission Ground Stations*

The mission ground stations uplink the commands for control of the spacecraft and accept the spacecraft's downlink telemetry of housekeeping and mission data. The ground stations are a part of ground operations that includes the antennas assigned to the mission and spacecraft contact.

This mission's polar orbit means that ground stations located at low- to mid-latitudes will be in contact for limited times each day. Depending upon geometry, perhaps only one contact on the ascending node and one contact on the descending node approximately twelve hours apart will occur each day. There will likely be a need for several ground stations, separated in longitude, if obligated to use those in low- to mid-latitudes. In between these ground contacts, the spacecraft is on its own and will need enough onboard memory to hold stored commands, housekeeping data, and mission data. Stored data can be downlinked during the next pass; however, if the contact is missed (delayed), the memory will continue to fill with more data. We expect that high data rates from the spacecraft to the ground are available to ensure that the stored data can be transmitted to the ground in the contact time available.

There are alternatives to using the mid-latitude ground stations. Because this is an international mission, with global participation and benefits, access to the high latitude ground stations listed below will be both beneficial in terms of international support and orbit geometry. These sites are listed because they are close to the poles of the Earth, which is where the all ground tracks of the spacecraft cross twice per orbit. Reference 4 [pages 885-887] gives these stations shown in Table 3. Figure 7 presents the Earth's map with two selected stations, near each pole, and their fields-of-view projected to 1,100 km altitude. Figure 8 presents the Earth's globe from the north and south poles. The two selected stations are shown along with the half-a-day's orbit tracks. Here, it is evident that every orbit crosses each pole and perhaps only one station at each pole will do the contact task.

### *Selection of Ground Stations*

The international participation serves as a reminder that the near-polar located mission ground stations are to be employed for this mission due to its orbit inclination. Select stations at Svalbard and McMurdo provide the uplink of commands and the downlink of spacecraft telemetry twice per orbit. This frequent contact is necessarily generous immediately after launch until the spacecraft is placed into a SAFE or ACTIVATION mode, which may be several days later. From this point until just before initiating the particle release only one contact per orbit is needed as the spacecraft is placed into OPERATIONAL mode. During dispensing and supporting maneuvers, both stations are to provide once per orbit coverage each to maintain communications as much as possible during the major activity of the mission. After dispensing is complete, coverage might reduce to one station each orbit, or less, only to resume with both stations during active secondary payload operations. Finally, as the orbit is lowered for reentry, both stations are to provide once per orbit coverage each to maintain communications as much as possible during this highly dynamic series of activities.

### *Selection of Mission Control Facility*

The flight operations team works in mission control. Several national facilities where the center can be located are at the Goddard Space Flight Center in Greenbelt, Maryland, United States; or the European Operations Centre in Darmstadt, Germany; or, the Russian Federal Space Agency in Korolyov, Russia. Each facility has supported LEO missions for decades and is thought to maintain the communication architecture to connect with the ground stations.

Table 3 — Ground Antenna Location Summary for Near-Polar Sites

| Station Name and Location | Latitude (approximate) | Longitude (approximate) | Network Ownership |
|---|---|---|---|
| Alaska Satellite Facility<br>The University of Alaska, Fairbanks | 65° N | 148° W | NASA's Near Earth Network |
| McMurdo Ground Station<br>McMurdo Station Antarctica | 78° S | 193° W | NASA's Near Earth Network |
| Svalbard Ground Station<br>Svalbard Norway | 78° N | 15° E | NASA's Near Earth Network |
| | | | |
| Poker Flat Alaska | 65° N | 147° W | PrioraNet |
| North Pole Alaska | 65° N | 147° W | PrioraNet |
| Inuvik Canada | 68° N | 134° W | PrioraNet |
| Esrange Sweden | 68° N | 21° E | PrioraNet |
| | | | |
| Tromsø Norway | 70° N | 19° E | Kongsberg Satellite Services |
| Svalbard Norway | 78° N | 15° E | Kongsberg Satellite Services |
| Troll Research Station Antarctica | 72° S | 3° E | Kongsberg Satellite Services |

Another alternative may be to use the space relay provided by the Tracking and Data Relay Satellite System, which is a constellation of several spacecraft that serve as a bent-pipe communications between user spacecraft and their ground-based mission control centers.

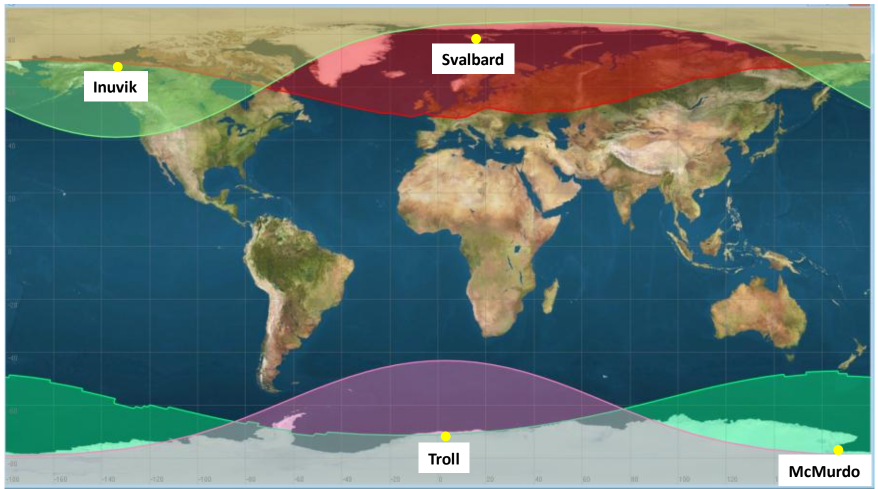


Fig. 7 — Selected Ground Stations Closest to Respective Poles

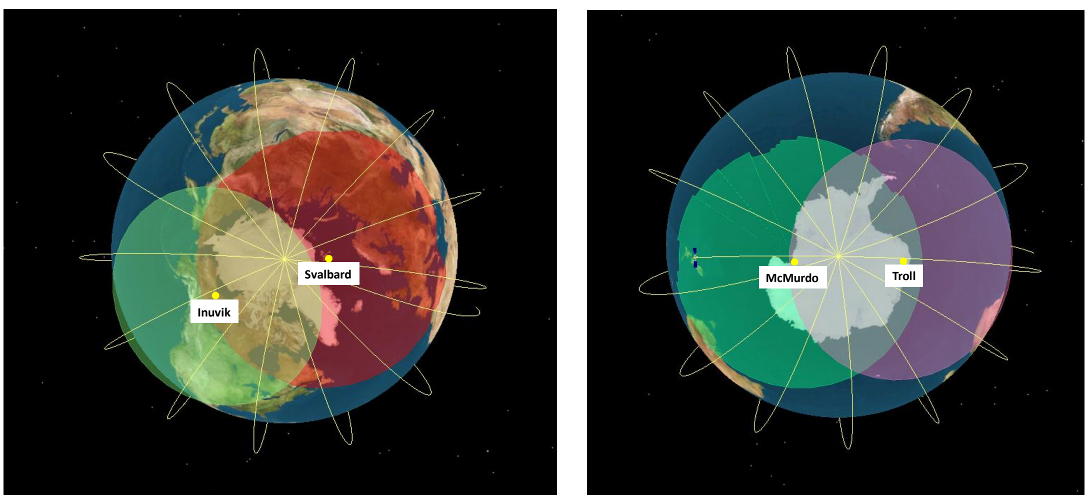


Fig. 8 — Selected Ground Stations Closest to Poles See Every Orbit Pass.
North Pole on left, South Pole on right

*Other Ground System Support*

Aside from the operations discussions above, other ground systems will support this mission. The international space community needs to be continuously notified of the whereabouts of the dust ring. They also need to know the success or lack of success of this scheme; that is, the effectiveness to remove small orbit debris (< 10 cm). The political and legal issues were very important before this mission to obtain international support and these issues are vital during the dispensing and ring decay. Finally the community will want to know when the ring decays as the particles reenter the atmosphere.

Ground-based or space-based sensors are needed to detect the ring's location and extent during the ring's lifetime. International understanding includes spacecraft avoiding the ring.

## OPERATIONAL SCENARIOS

Concept of operations preparation guides state the need for inclusion of the description of the operational scenarios. Scenarios review the normal and the many abnormal or contingency operations. These are a step-by-step description of how the proposed system should operate and interact with its users and its external interfaces under a given set of circumstances. Scenarios allow readers to walk through them and gain an understanding of how all the various parts of the proposed system function and interact. Scenarios attempt to bind all the individual parts of a system into a comprehensible whole and to see how all the pieces interact to provide operational capabilities [1, p. 14].

As stated earlier, there are several other research areas being pursued to better size the payload and its dispensing scheme. The efficiency of these hypervelocity collisions between the tungsten particles and the presumed aluminum debris, to vaporize some of the debris, is yet to be determined, which will guide the selections of the particle diameter and total mass flown. The resulting lifetime of the mission of these tiny particles can then be estimated. Additional research into the possible dispenser mechanism and its ability to shoot the particles with the suggested velocity distribution is to be determined.

Discussed in the chapter on legal and international issues, is the international acceptance that this mission to provide small debris remediation requires support from the world-wide space community. Support must begin years before the launch and continue past mission lifetime as the merits of the mission continue to be discussed.

We expect that spreading the work among multiple space nations will help garner wide support, international cooperation, and the attendant international-sized headaches. We expect this mission will play to the media and might educate and fascinate the population and motivate younger people in general [4, p. 799].

### *Pre-Launch*

The launch site is likely to be selected for several reasons including geographic location to support the orbit inclination, launch towers that support the larger rockets needed for this heavy spacecraft, and facilities to process the spacecraft. To save transportation costs, the spacecraft payload of 10,000 kg of tungsten spheres or the structural dispenser loaded with the spheres could be delivered from the manufacturer directly to the launch site. Should the Delta IV or Atlas V be selected for this mission, then the launch site is going to be Vandenberg Air Force Base in California or should the Ariane 5 be selected, then the launch site is going to be Kourou, French Guiana.

The spacecraft arrives at the launch site in the OFF mode and is placed in the processing facility. The ground support equipment is connected to ensure the spacecraft made the trip from the factory to the processing facility successfully. Integration and Test begins with tungsten sphere loading (if necessary), ordinance installation, and some thermal blanket closeout.

The spacecraft is again powered on and temporarily connected to the mission control facility, via communications links, for pre-launch testing of commanding the spacecraft. Final mission dress rehearsals occur at the control facility. The ground stations will go through pre-launch readiness tests with the control facility.

Another shipping container is provided during the ferry of the spacecraft to the launch pad and for the crane operations to lift the container to the top of the rocket. The spacecraft attach fitting is mated to the rocket, final thermal blankets are installed or closed, the spacecraft is turned on for final checks, and remove before flight items and final closeouts occur.

### *Launch*

On launch day, the spacecraft is disconnected from cabling. It may be on internal battery power to maintain the receiver always on. We assume the launch countdown proceeds well and the launch vehicle inserts the dispenser spacecraft into the mission orbit. There may be temporary ground stations along the launch trajectory following the telemetry stream from the launch vehicle indicating the quality of the flight in terms of trajectory and event milestones.

Soon the spacecraft is separated from the rocket's last stage as it passes over the mission ground station, the receiver waits for the transmitter turn on command. The launch vehicle team transmits their estimate of the injection orbit to the mission control facility. The ground station receives the telemetry from the spacecraft and via communications lines send the data to the mission ground station.

### *Early Mission Rectification and Operations*

Orbit determination begins. The spacecraft enters ACTIVATION mode. Solar arrays are deployed (if necessary), and some instruments are turned on. Commands routinely flow to the spacecraft and science, engineering, and housekeeping data flow to the ground. These flows occur only when contact is made with the ground station, which can now get into a routine schedule. ACTIVATION may take several days with the entire engineering team confirming accurate data decommutation on their telemetry screens and expected values of their telemetry points.

After completion of ACTIVATION mode, the spacecraft transitions to OPERATIONAL mode because it is now fully functional. By now, it should be apparent if the spacecraft needs to maneuver to correct launch injection errors. These thrust burns can be scheduled. If there are secondary payloads to measure the particle density or particle flux, then these background (or, laboratory control) measurements can begin well before particle dispensing begins. This is envisioned as taking several weeks as the spacecraft orbits at 1,100 km.

### *Dispensing Operations – Primary Mission Goal*

Finally, after years of preparation, the primary mission goal occurs – dispensing the trillions of tungsten spheres. Perhaps the design has 6 separate dispensing events each pushing about 1,700 kg of particles. There are likely to be sensors that monitor the outward flow of particles. As these particles are pushed out nearly along the spacecraft's negative velocity vector, this causes them to initially move lower and behind the spacecraft. As the motion progresses, these particles move ahead the spacecraft because the particles are in a slightly lower altitude orbit. Cameras might image the dispensing operations.

The release of the particles causes the mass properties to significantly change. The spacecraft's attitude control system expects this change and accommodates with modifications to its parameter list within the controlling software.

The basic release strategy copied from our earlier paper suggests the spacecraft might maneuver 60° in true anomaly before the next dispensing, and so on. Perhaps further analysis will show maneuvering to be unnecessary because waiting for the previous group of particles to move away may be just as effective. Dispensing continues until all containers are empty, which may take several days to complete.

The spacecraft can continue in the same orbit as there is little relative motion between the spacecraft and the particles. Should there be no secondary payloads to measure density or flux; the spacecraft might begin deorbit operations.

Further description of the remaining dispensing operations is postponed until more is known about the dispenser. A strategy consistent with the total tungsten mass needs to be determined. Additionally, the scheme must include results from analysis of determining if the spacecraft's orbit is significantly disturbed by the negative $\Delta V$ imparted due to particle release. It may have to maneuver to reestablish the circular orbit in addition to relocate in true anomaly.

### *Density Measurement Operations – Secondary Mission Goal*

This section can be better completed after further investigation into possible methods of making the density or flux measurements. Noting there is little relative motion between the now empty dispenser spacecraft and the tungsten particles it may be difficult to take measurements from the spacecraft. In general, these sensors expect a large relative motion between sensor and particle such that the particle penetrates a detection sheet or passes through an ionization device.

There are small meteoroids and natural dust that will be within the orbiting ring. The sensor must be able to distinguish the qualities of tungsten particles to allow for reliable results. It may be that comparing these measurements with those taken several weeks before dispensing shows no statistically significant differences.

If significant relative motion must be achieved, then a very expensive means of obtaining this secondary goal is to fly another spacecraft sensor suite in an orbit that crosses the tungsten ring. For example, flying the second spacecraft at 1,100 km circular and 0°, or 28.5°, or some other inclination far removed from 90° will provide a few seconds of data collection, possibly twice per orbit. There will likely be many passes through the ring that produce no detections of tungsten owing to the low density.

Another investigation could be pursued into a ground-based measurement scheme to estimate the tungsten density. One concept is the photoelectric effect, whereby electrons are emitted from solids when they absorb energy from light, if the energy from the photon is large enough. Perhaps this can be measured from the ground and be used to estimate tungsten density.

#### *Deorbit the Dispenser Spacecraft*

After the spacecraft mission is complete, it is time to deorbit and not become orbit debris. The propulsion system is used to lower the spacecraft altitude below that of the International Space Station, which varies in the range of 320-420 km at 51.6° inclination. From this lower orbit, say 300 km circular, the spacecraft can be more easily targeted for a controlled ocean splashdown by then lowering perigee deep in the atmosphere. Targeting for the oceans avoids risk to humans and landmasses. A recent description of a controlled reentry is presented in References 12 and 13.

A significant component to the overall weight of the spacecraft includes the quantity of propellant, the thruster, and the remaining plumbing components of the propulsion system for earlier maneuvering and for deorbit. The thruster force should be large enough to quickly perform the maneuver so as to rapidly pass through the space station orbit and Earth's atmosphere.

**GUIDELINES**

Two more tables are presented here to record summary points. Table 4 summarizes some parameters and their values presented earlier that motivated this orbit debris remediation scheme and allowed some analysis to proceed. These values were earlier proposed in previous papers and trade studies. This Concept of Operations document is not a requirements document (although a requirements document may flow from the concept of operations). Table 5 summarizes some discussion within this document that indicates further research is needed before this Concept of Operations document can be expanded and released.

Table 4 — Summary of Parameters and Values Earlier Presented

| Guidelines – NOT Requirements | possible change upon further research |
|---|---|
| tungsten | probably not |
| 30 micron diameter sphere of tungsten | to be determined by the user |
| tolerance ± 2 microns | maybe |
| 10,000 kg of particles | maybe |
| 1,100 km circular 90° inclination | probably not |
| altitude tolerance ± 50 km<br>inject to 1,100 km ± 50 km | yes |
| eccentricity < 0.001337<br>(± 10 km) tolerance | probably not |
| ± 0.1° inclination tolerances | maybe |
| right ascension of ascending node<br>no guideline | maybe |
| ability of ring to stay intact over its lifetime | no |
| dust release opposite spacecraft's in-track path | no |

Table 5 — Research Topics to Complete Before Final Version of Concept of Operations Can Be Written

| Topic | Description |
|---|---|
| $\kappa$ | kappa is the term defined in our previous research papers describing the efficiency of hypervelocity collisions between the tungsten particles and debris, which establishes the total mass of the tungsten spheres and their diameter |
| dispenser mechanism | the selected mechanism and its ability to dispense the tungsten spheres with the desired flux ($kg/m^2$-s) and velocity distribution will have an iterative role in the design of maneuvers supporting the dispensing activities |
| | |
| abnormal operations | developing and documenting myriad abnormal operations, or contingency operations, and how to return to normal operations |
| | |
| location of ring | Further research is needed to determine if the ring can be detected by the radio or the electromagnetic radio frequency interference it creates, if any. |
| | |
| possible secondary payloads | what device might directly estimate or provide data to estimate the orbiting density of the particles or the particle flux,<br>might the secondary payload fly on another spacecraft that intersects the tungsten ring |
| | |
| a second spacecraft | to assist with "seeing" the ring, a secondary spacecraft orbits to allow its sensors to view the entire ring's integrity |

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